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EXPERIMENTAL INVESTIGATION ON INFLUENCE OF FUNCTIONALIZED MULTI-WALLED CARBON NANOTUBES ON SURFACE ROUGHNESS IN DRILLING OF CFRP COMPOSITES

SWAPNIL SUMAN, P PANCHAM ALVA, NOEL GEORGE DANIEL & NAGARAJA SHETTY

Department of Mechanical and Manufacturing Engineering, Manipal Institute of Technology, MAHE, Manipal, India

ABSTRACT

This paper presents the effect of carboxyl functionalised multi-walled carbon nanotubes on the surface roughness of drilled holes in carbon fibre reinforced plastic (CFRP) laminates. Drilling tests were conducted on CFRP laminates fabricated with neat and carboxyl functionalised multi-walled carbon nanotubes filled epoxy matrix. The drilling process parameters evaluated are feed rate, spindle speed, point angle and drill diameter. The surface roughness of the drilled holes' wall was measured. Response surface methodology approach was used to analyse the effect of cutting parameters. Surface roughness was found to increase on increasing the feed rate, point angle and drill diameter while it decreased with an increase in spindle speed. An average reduction of 27.96% in surface roughness was observed when carboxyl functionalised multi-walled carbon nanotubes were used as a filler.

KEYWORDS: Surface Roughness, Multi-Walled Carbon Nanotubes, Response Surface Methodology, Drilling, CFRP

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Original Article

INTRODUCTION

Over the recent years, the utilization of composites such as carbon fibre reinforced polymer has been on the ascent in automobile, aerospace, aircraft and naval industries due to their exceptional properties like high strength, low weight and high stiffness[1-3]. When components are subjected to precision fits, fastener holes and fatigue load, the surface finish of the drilled hole is considered to be a significant parameter [4,5]. Hence, analysing and measuring surface roughness (R_a) of the machined hole plays a crucial role in manufacturing such parts. Drilling of CFRPs induces damages such as delamination, spalling[6,7], fibre pull-out and crack formation[8], which leads to poor surface finish. Surface finish of machined parts has a major influence on their performance [9].

Durão et al.[10] compared feeds and different drill point geometries in CFRP and found that twist drills gave smoother finish, though the influence of feed was not stated. Ramulu et al. [11] concluded from their study on machining polymer composites that with increase in cutting speed, the surface finish improved. Isik [12] found that the surface roughness of a unidirectional fibre reinforced plastic was less affected by the depth of cut, although the cutting speed and feed rate had more influence. Takeyama et al. [13] found that with an increase in feed rate, the damage around holes and surface roughness also increased. According to Latha et al. [14], feed rate is found to have the maximum influence on the surface roughness.

Palanikumar[15] found that feed rate was the parameter which affected surface roughness the most, but drill diameter didn't have as much an influence when compared to feed rate. Similarly, Tsao et al. [16] found that

feed rate and spindle speed had the greatest contribution to surface roughness, when compared with drill diameter, using candle stick drill bit. An et al. [17] found that tool material and tool geometry had a prominent role in determining the surface roughness. Bandhu et al. [18] concluded that during drilling, a combination of low feed rate, low point angle and high spindle speed resulted in better surface finish. Nagaraja et al. [19] showed that titanium nitride (TiN) coated solid carbide twist drill bits caused less damage than uncoated solid carbide drill bits in drilling of CFRPs.

Florian et al. [20] concluded that inclusion of carbon nanotubes (CNT) as fillers to the epoxyresin enhanced the stiffness, strength and fracture toughness of the composite material. This was attributed to CNTs acting as anagent in stress transformation between the fibre and the matrix. Kumar et al.[21]investigated surface roughness ofmulti walled carbon nanotubes(MWCNTs) modified CFRP. They concluded that minimum and maximum surface roughness was observed at 1.5 wt.% and 0.5 wt.% of MWCNTs modified carbon/epoxy polymeric nano composite material. They also observed that surface roughness at the entrance is more than that at the exit and increased with an increase in spindle speed and feed rate. The main barrier to enhance properties of nano composites is poor dispersion of CNTs which leads to agglomeration and voids in the composite [22]. For proper dispersion of CNTs, techniques like sonication, magnetic stirring, high shear mixing and mechanical stirring are utilized [23]. In addition to it, Gojny et al. [24] found that the surface chemical functionalization of the MWCNTs increased its dispersion in the epoxy matrix. Covalent groups like carboxyl, glycidyl, and amino groups functionalized with CNTs facilitate covalent bonding between the epoxy matrix and CNTs resulting in better interfacial bonding[25].

The influence of different combinations of machining parameters is suitably predicted by central composite design (CCD) along with response surface methodology (RSM)[26]. RSM is a statistical approach to develop empirical models and optimize responses. It is able to decide and exhibit the association with other input control variables through regression analysis and application of experiments[27].

This study aims to investigate the effect of carboxyl functionalized multi walled carbon nanotubes (COOH-MWCNTs) on surface roughness of CFRPs and compare it with the neat composite. The holes were drilled with TiN coated solid carbide twist drill bit. Drill diameter, feed rate, point angle and spindle speed were taken as machining parameters and were analysed with RSM.

MATERIALS AND METHODS

Fabrication of Composite

Bi-directional carbon fibre of 200 GSM wasobtained from Arrow Technical Textiles Pvt. Ltd., Mumbai, India. Epoxy resin LY556 along with hardener HY951was obtained from Singhal Chemical Corporation, Uttar Pradesh, India. The MWCNTs used were surface functionalised with carboxyl groups (-COOH)obtained from Platonic Nanotech Private Limited, Jharkhand, India, with a degree of functionalisation of 10% and diameter in the range of 12-15 nm and length in the range of 3-10 microns. The MWCNTs had a purity greater than 97%. Two specimens were prepared, one with MWCNTs filled epoxy matrix and the other with neat epoxy. The MWCNTs were added to the epoxy, 0.3% by weight and dispersed using an ultrasonicator{Grant XUBA 3 Ultrasonic water bath} for half an hour to get a homogeneous mixture. Epoxy and hardener were then mixed in 10:1 ratio. Hand lay-up process was used to fabricate the laminates at room temperature, maintaining the resin content at 45% by weight and carbon fibre at 55% by weight followed by vacuum bagging for 24 hours at room temperature. The dimensions of the fabricated composite were 200mm x 200mm x 5mm. The post curing process was gradually carried out at temperatures 50°C, 70°C and 85°C in time intervals of 30, 60 and 120

minutes respectively in a hot-air oven.

Design of Experiments using Response Surface Methodology (RSM)

Response surface methodology is used to design the experimental layout. It is a collection of statistical tools which helps in designing, analysing and optimising the responses. Here, central composite design is used because it can establish relationship between the response and the parameters with least number of experiments without loss of accuracy [28]. The response in drilling of CFRP compositesis represented by "y" which is called the response surface given by:

$$y = f(A, B, C, D) \tag{1}$$

The general form of the second order model is chosen for which the approximating function is given by:

$$y = \delta_0 + \delta_1 A + \delta_2 B + \delta_3 C + \delta_4 D + \delta_{11} A^2 + \delta_{22} B^2 + \delta_{33} C^2 + \delta_{44} D^2 + \delta_{12} AB$$
$$+ \delta_{13} AC + \delta_{14} AD + \delta_{23} BC + \delta_{24} BD + \delta_{34} CD \tag{2}$$

where, δ_0 is the constant term, δ_i are the linear terms, $\delta_{ii}$are the square terms and δ_{ij} represents the interaction between the parameters. In this experiment, the four parameters drill diameter, feed rate, point angle and spindle speed were investigated at three levels. The parameters and the levels used are shown in Table 1. MINITAB 14.0software was used to design the experiments, obtain coefficients of equation (2) and to optimise the response. In this particular case, the design called for 30 experiments with 4 parameters which are shown in Table 2.

Table 1: Levels of Drilling Parameters

Symbol	Parameters	Level 1	Level 2	Level 3
A	Spindle Speed (rpm)	1200	1500	1800
B	Feed Rate (mm/min)	10	15	20
C	Point Angle (degree)	90	104	118
D	Drill Diameter (mm)	4	6	8

Experimental Procedure

The drill bits used in this experiment were TiN coated solid carbide twist drill bits as shown in Figure 1. Computer numerical control (CNC) machine {AMC DTC 300 Vertical Machining Centre} was used to perform the drilling operation as shown in Figure 2. Support plates were placed under the specimen to prevent damage during drilling [29]. Taylor-Hobson Surtronic 3+ instrument was used to measure the surface roughness as shown in Figures 3(a) and 3(b). Surface roughness was measured at 4 different locations on the surface of the drilled hole and the average was taken.

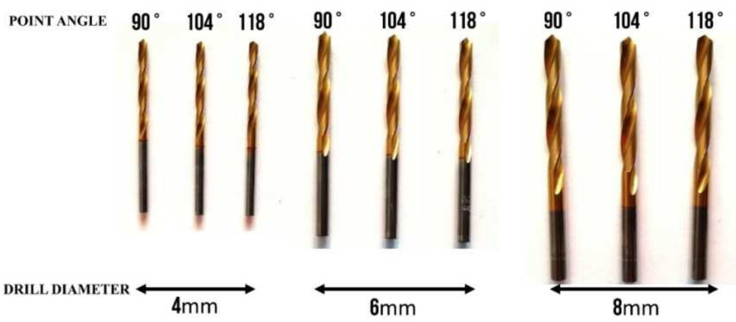


Figure 1: Dimensions of Twist Drill Bits Used

Figure 2: Drilling of Holes in CFRP using CNC Vertical Machining Centre

(a) (b)

Figure 3 (a): Taylor-Hobson Surtronic 3+ Instrument
(b) Measurement of Surface Roughness of the Drilled Hole Surface

Table 2: Experimental Design Layout using RSM

Spindle Speed(rpm)	Feed Rate(mm/min)	Point Angle(degree)	Drill Diameter(mm)
1200	10	90	4
1800	10	90	4
1200	20	90	4
1800	20	90	4
1200	10	118	4
1800	10	118	4
1200	20	118	4
1800	20	118	4
1200	10	90	8
1800	10	90	8
1200	20	90	8
1800	20	90	8
1200	10	118	8
1800	10	118	8
1200	20	118	8
1800	20	118	8
1500	15	104	6

Table 2: Contd.,			
1500	15	104	6
1500	15	104	6
1500	15	104	6
1200	15	104	6
1800	15	104	6
1500	10	104	6
1500	20	104	6
1500	15	90	6
1500	15	118	6
1500	15	104	4
1500	15	104	8
1500	15	104	6
1500	15	104	6

RESULTS AND DISCUSSIONS

Correlation between Surface Roughness and Cutting Parameters

Using quadratic response surface modelling, the correlation between surface roughness and drilling parameters were obtained. The equations in uncoded units can be written as follows:

- **CFRP without Nanotubes**

$$R_a = 0.453586889 + 0.001288799 * A + 0.020076118 * B + 0.004652134 * C + 0.253672439 * D - 6.83502e\text{-}07 * A^2 - 0.001060606 * B^2 - 3.32406e\text{-}05 * C^2 + 0.008371212 * D^2 + 1.08333e\text{-}05 * A * B + 5.65476e\text{-}06 * A * C - 9.16667e\text{-}05 * A * D + 0.000160714 * B * C + 0.0005 * B * D - 0.000803571 * C * D \quad (3)$$

R^2=0.95 Adjusted R^2=0.903

- **CFRP with nanotubes**

$$R_a = 0.794511802 + 0.001060576 * A + 0.042438672 * B - 0.021624665 * C + 0.29733676 * D - 4.57912e\text{-}07 * A^2 - 0.001448485 * B^2 + 9.58565e\text{-}05 * C^2 + 0.00344697 * D^2 + 2.5e\text{-}06 * A * B + 3.27381e\text{-}06 * A * C - 0.000116667 * A * D + 0.000178571 * B * C + 0.001375 * B * D - 0.000223214 * C * D \quad (4)$$

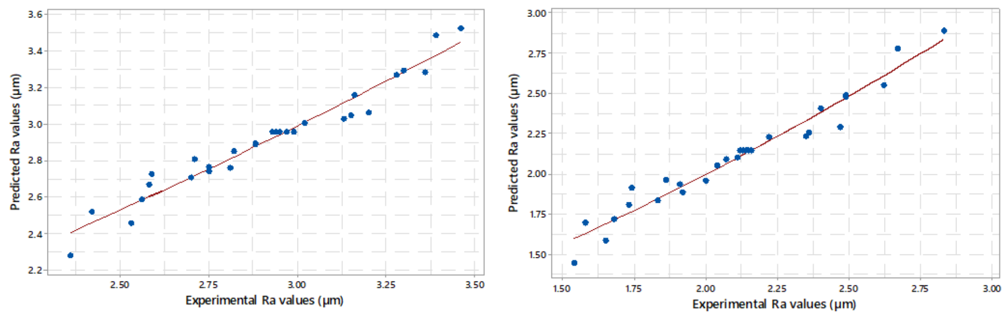
R^2=0.953 Adjusted R^2=0.908

where, A is the spindle speed in rpm, B is the feed rate in mm/min, C is the point angle in degrees and D is the drill diameter in mm.

The average surface roughness values obtained experimentally, predicted surface roughness values obtained by RSM and percentage errors are shown in Table 3. The comparison of the experimental values of R_a with the predicted values are presented as scatter plots in Figure 4(a) and Figure 4(b). A good correlation between the experimental and predicted values is seen and this can be attributed to the high value of R^2, indicating an excellent goodness of fit. Residual analysis is used to check the accuracy of the model [26]. The normal probability plots for surface roughness as shown in Figure5(a) and 5(b), illustrate that the residuals are spread along an almost straight line, indicating that the errors have normal distribution.

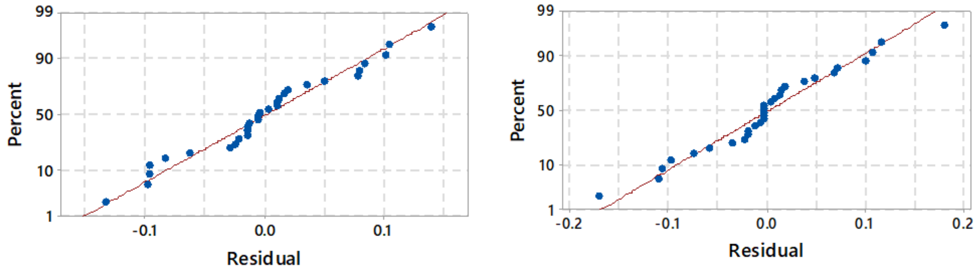
Table 3: Experimentally obtained and RSM Predicted Values for Surface Roughness

	Surface Roughness without Nanotubes, µm			Surface Roughness with Nanotubes, µm		
Test No.	Experimental	Predicted	Error%	Experimental	Predicted	Error%
1	2.56	2.58	0.78	1.68	1.72	2.38
2	2.36	2.28	3.39	1.54	1.44	6.49
3	2.81	2.76	1.78	2	1.95	2.50
4	2.42	2.52	4.13	1.58	1.69	6.96
5	2.58	2.66	3.10	1.73	1.80	4.05
6	2.53	2.45	3.16	1.65	1.58	4.24
7	2.88	2.89	0.35	2.07	2.09	0.97
8	2.75	2.74	0.36	1.92	1.88	2.08
9	3.3	3.29	0.30	2.49	2.49	0.00
10	2.75	2.76	0.36	1.91	1.93	1.05
11	3.39	3.49	2.95	2.67	2.78	4.12
12	3.13	3.03	3.19	2.35	2.24	4.68
13	3.36	3.28	2.38	2.62	2.55	2.67
14	2.82	2.85	1.06	2.04	2.05	0.49
15	3.46	3.52	1.73	2.83	2.89	2.12
16	3.16	3.16	0.00	2.4	2.40	0.00
17	2.94	2.96	0.68	2.13	2.14	0.47
18	2.93	2.96	1.02	2.12	2.14	0.94
19	2.95	2.96	0.34	2.16	2.14	0.93
20	2.99	2.96	1.00	2.14	2.14	0.00
21	3.2	3.06	4.38	2.47	2.29	7.29
22	2.59	2.72	5.02	1.74	1.91	9.77
23	2.71	2.81	3.69	1.86	1.96	5.38
24	3.15	3.05	3.17	2.36	2.25	4.66
25	2.88	2.89	0.35	2.11	2.10	0.47
26	3.02	3.00	0.66	2.22	2.23	0.45
27	2.7	2.71	0.37	1.83	1.83	0.00
28	3.28	3.27	0.30	2.49	2.48	0.40
29	2.97	2.96	0.34	2.15	2.14	0.47
30	2.94	2.96	0.68	2.14	2.14	0.00
Average Error			**1.71**			**2.53**



(a) (b)

Figure 4: Comparison of Experimental and Predicted Surface Roughness of CFRP– (a) without Nanotubes (b) with Nanotubes

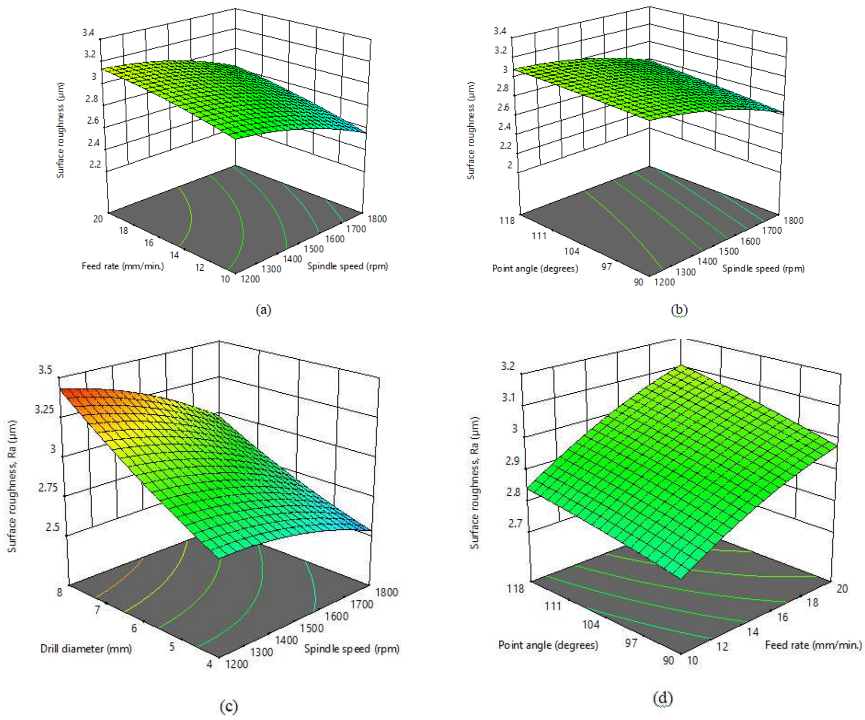


(a) **(b)**

Figure 5: Normal Probability Plots for Surface Roughness of CFRP– (a) without Nanotubes (b) with Nanotubes

Response Surface Analysis

The effects of spindle speed, feed rate, point angle and drill diameter on surface roughness are shown by plotting 3D response surface plots. The response plots are shown in Figures6 (a)-(f) and 7 (a)-(f) for CFRP without nanotubes and CFRP with nanotubes respectively. Two variables are used for each surface plot with surface roughness as the response and keeping the other two variables at constant middle level. The response surfaces obtained are observed to be similar for both CFRP with neat epoxy and CFRP containing epoxy with CNTs. By examining these plots it is inferred that surface roughness decreases with an increase in spindle speed. A higher spindle speed can remove the effect of built up-edge leading to a better surface finish and lower surface roughness [30]. The increase in feed rate, point angle and drill diameter increases the surface roughness. Higher feed rates lead to higher rate of thrust acting on the composite material, producing high surface roughness [31]. A higher drill diameter leads to a higher material removal rate increasing the thrust force and the surface roughness. The increase in point angle also leads to an increase in thrust force resulting in an increased surface roughness [32].



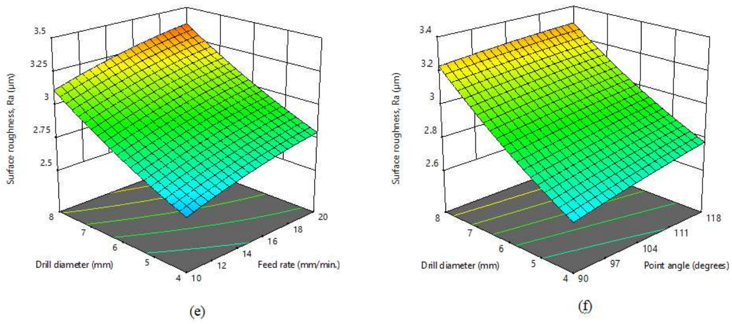


Figure 6(a)-(f): 3D Response Surface Plots of Surface Roughness of CFRP without Nanotubes

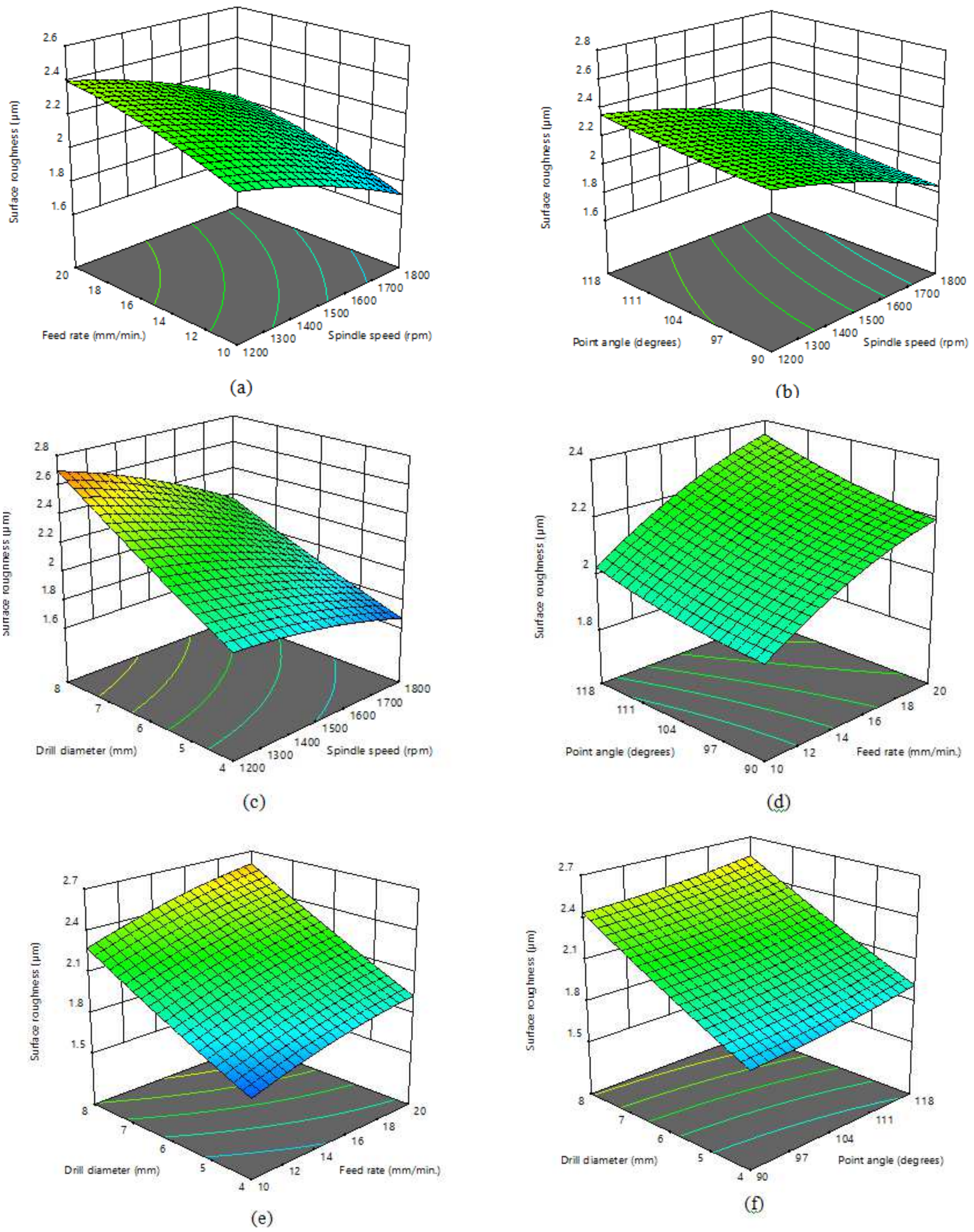


Figure 7(a)-(f): 3D Response Surface Plots of Surface Roughness of CFRP with Nanotubes

Optimization of Response

The manufacturing experiments aim to obtain the desired R_a values corresponding to the optimum combination of drilling parameters [33]. Response surface optimization can be used to determine the best combination of machining parameters and tool geometry. Here, the surface roughness has to be minimised. Figures 8 and 9 show the RSM optimization result for R_a. The optimum parameters obtained are a spindle speed of 1800 rpm, feed rate of 10 mm/min, point angle of 90 degrees and drill diameter of 4 mm for both CFRP without nanotubes and CFRP with nanotubes.

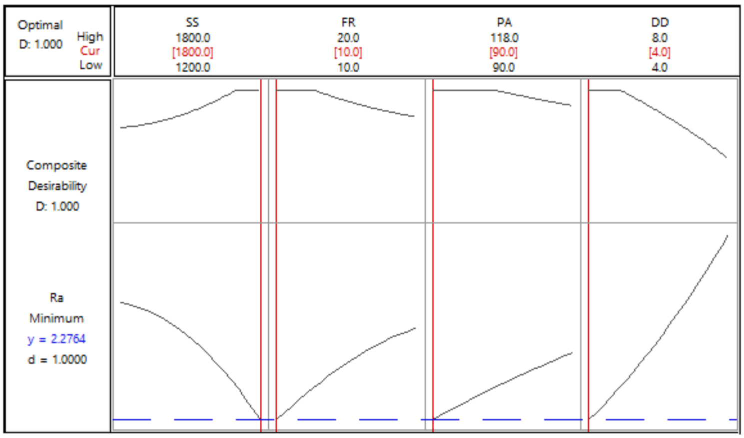


Figure 8: Surface Roughness Response Optimisation Plot for CFRP without Nanotubes

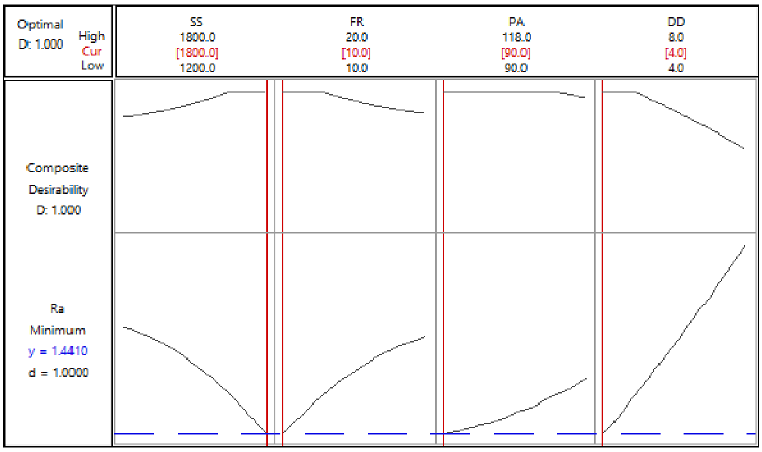


Figure 9: Surface Roughness Response Optimisation Plot for CFRP with Nanotubes

Confirmation Test

The optimization result obtained from RSM is validated by carrying out confirmation test for the optimum parameters (A_3 = 1800 rpm, B_1 = 10 mm/min, C_1 = 90 degrees and D_1 = 4 mm). The confirmation test results are presented in Table 4. The surface roughness measured is found to be in close agreement with the value predicted by RSM, with percentage errors of 3.39 for CFRP without nanotubes and 6.49 for CFRP with nanotubes respectively.

Table 4: Confirmation Test Results for Surface Roughness

Material	Optimum Cutting Parameters	Experimental R_a	Predicted R_a	Error %
Neat CFRP	$A_3B_1C_1D_1$	2.36	2.28	3.39
CFRP with MWCNTs	$A_3B_1C_1D_1$	1.54	1.44	6.49

A_3 = 1800 rpm B_1 = 10mm/minC_1 = 90 degreesD_1 = 4mm

Validation Test

The adequacy of the model developed is checked by performing the validation test. The process parameters chosen for validation test are shown in Table 5. All the eight confirmation experiments have set of process parameters that have not been used previously, but are within the experimental range. MINITAB 14.0 is used to predict the surface roughness of the selected experiments using the developed RSM model. Table 6 shows the actual experimental values, predicted values and percentage errors for CFRP without nanotubes and CFRP with nanotubes. The average errors of prediction are3.85% for CFRP without nanotubes and 4.56% for CFRP with nanotubes. From the low values of the average errors obtained, it can be said that the RSM model is fairly accurate.

Table 5: Experimental Layout for Validation Tests

Test No.	Spindle Speed, rpm	Feed Rate, mm/min	Point Angle, Degree	Drill Diameter, mm
1	1200	10	90	6
2	1200	10	104	8
3	1200	20	118	6
4	1500	10	90	6
5	1500	15	118	8
6	1500	20	104	8
7	1800	10	104	6
8	1800	15	118	4

Table 6: Comparison of Experimental and RSM Predicted Results of Surface Roughness for the Validation Tests

	Surface Roughness without Nanotubes, μm			Surface Roughness with Nanotubes, μm		
Test No.	Experimental	RSM Predicted	Error%	Experimental	RSM Predicted	Error%
1	2.71	2.9	7.01	1.61	1.74	8.07
2	3.45	3.29	4.64	2.32	2.26	2.59
3	3.32	3.17	4.52	2.78	2.82	1.44
4	2.91	2.76	5.15	1.63	1.74	6.75
5	3.26	3.29	0.92	2.04	2.10	2.94
6	3.34	3.37	0.90	2.60	2.69	3.46
7	2.42	2.56	5.79	1.62	1.50	7.41
8	2.67	2.62	1.87	2.09	2.01	3.83
Average Error			**3.85**			**4.56**

Comparison of Surface Roughness of Neat and COOH-MWCNT CFRP Composite

Table 7 represents the R_a values of CFRP without nanotubes and CFRP with nanotubes. It can be seen from the table that the addition of COOH-MWCNT leads to an average 27.96 % decrease in surface roughness. In the drilling of CFRP doped with MWCNTs, less matrix cracking and less formation of built-up edge on the hole wall takes place leading to a better surface finish.

Table 7: Surface Roughness of Neat and COOH-MWCNT CFRP Composite

Test No.	Surface Roughness without Nanotubes, μm	Surface Roughness with Nanotubes, μm	% Decrease
1	2.56	1.68	34.38
2	2.36	1.54	34.75
3	2.81	2	28.83
4	2.42	1.58	34.71

Table 7: Contd.,			
5	2.58	1.73	32.95
6	2.53	1.65	34.78
7	2.88	2.07	28.13
8	2.75	1.92	30.18
9	3.3	2.49	24.55
10	2.75	1.91	30.55
11	3.39	2.67	21.24
12	3.13	2.35	24.92
13	3.36	2.62	22.02
14	2.82	2.04	27.66
15	3.46	2.83	18.21
16	3.16	2.4	24.05
17	2.94	2.13	27.55
18	2.93	2.12	27.65
19	2.95	2.16	26.78
20	2.99	2.14	28.43
21	3.2	2.47	22.81
22	2.59	1.74	32.82
23	2.71	1.86	31.37
24	3.15	2.36	25.08
25	2.88	2.11	26.74
26	3.02	2.22	26.49
27	2.7	1.83	32.22
28	3.28	2.49	24.09
29	2.97	2.15	27.61
30	2.94	2.14	27.21
Average Decrease			**27.96**

CONCLUSIONS

In this paper RSM analysis was carried out to investigate the effects of spindle speed, feed rate, point angle and drill diameter on surface roughness of drilled holes in CFRP with and without MWCNTs. The effect of using MWCNTs functionalised with COOH as filler in CFRP on surface roughness was studied. The following results were observed:

- Second order predictive equation was developed using quadratic response surface modelling for estimating surface roughness (R_a) and high values of correlation coefficient (R^2), 0.95 for neat CFRP and 0.953 for COOH-MWCNT CFRP were calculated. These high values of R^2 suggest models with high accuracy.
- The optimum combination of drilling parameters for minimum surface roughness was found to be a spindle speed of 1800 rpm, feed rate of 10 mm/min, point angle of 90 degrees and drill diameter of 4 mm.
- 3D response surface plots were generated to study the effect of the parameters on surface roughness. It was found that surface roughness decreased with an increase in spindle speed, while it increased with an increase in feed rate, point angle and drill diameter.
- The addition of COOH-MWCNTs to CFRP led to a better surface finish and an average decrease of the surface roughness by 27.96%. This was attributed to less matrix cracking and less formation of built-up edge on the hole wall.

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